

# Possible Origin Of The Neutrino Speed Anomaly Reported By OPERA

Shlomo Dado and Arnon Dar  
*Department of Physics, Technion, Haifa 32000, Israel*

Recently the OPERA collaboration reported a measurement of a superluminal speed of muon neutrinos traveling through the Earth's crust between their production site at CERN and their detection site under Gran Sasso,  $\sim 730$  km away. The measurement was based on the assumption that the pulse shape of the neutrinos from the decay of parent mesons produced in proton-target collisions is the same as that of the incident protons. Here we argue that the effective column density of the target along the beam direction decreases with time during the  $10.5 \mu\text{s}$  duration of the proton pulse. This is because of the thermal expansion and expulsion of target material along the beam by the energy-momentum deposition during the  $10.5 \mu\text{s}$  pulse. The progressive reduction in the effective column density during the pulse decreases the neutrino production rate per incident proton. It could have advanced the mean production time of the detected neutrinos relative to that calculated from the proton pulse-shape, by an amount comparable to the measured neutrino lead time  $60.7 \pm 6.9(\text{stat}) \pm 7.4(\text{sys})$  ns. This explanation implies that the planned measurements by OPERA of the speed of neutrinos produced in much shorter (a few ns) pulses, should yield a speed consistent with the speed of light in free space.

PACS numbers:

## I. INTRODUCTION

The OPERA collaboration has reported recently [1] a measurement of a superluminal speed  $(v/c - 1) = [2.48 \pm 0.28(\text{stat}) \pm 0.30(\text{sys})] \times 10^{-5}$  of muon neutrinos traveling through earth between their production site at CERN and their detection site under Gran Sasso,  $\sim 730$  km away. However, the OPERA measurement of the neutrino speed was not based on the time difference between the production and detection of individual neutrinos but rather on the measured distribution of arrival times of neutrinos at Gran Sasso with respect to the waveform of the pulsed protons entering the CERN Neutrino to Gran Sasso (CNGS) system. Although the distance  $d$  from the target where the parent meson produces the neutrino in the decay tunnel is unknown, this introduces negligible difference between the time that a proton enters the CNGS system and the time that the produced neutrino enters the OPERA detector under the Gran Sasso,

$$dt \approx d/2c\gamma_m^2 \sim \tau_m/2\gamma_m \lesssim 0.1 \text{ ns} \quad (1)$$

for pions of lifetime  $\tau_m = \tau_\pi \approx 2 \times 10^{-8}$  s and Lorentz factor  $\gamma_m = \gamma_\pi \geq 100$ .

The neutrino speed that was inferred by OPERA was based on the assumption that the probability to produce the parent meson in the target is the same for all the protons in the pulse, and hence, the temporal profile of the neutrino pulse is faithfully represented by temporal profile of the proton pulse. However, this may not be the case because of the large energy-momentum deposition in the graphite target along the beam during the  $10.5 \mu\text{s}$  proton pulse. This large energy-momentum deposition in the target, as we shall argue below, probably reduces the meson production rate for late incident protons during a pulse due to thermal expansion and expulsion of target

material from the beam path. This can advance the mean production time of the neutrinos relative to the mean time of the proton pulse by the neutrino 60.7 ns lead time that was inferred by the OPERA collaboration.

## II. THE NEUTRINO PRODUCTION RATE PER INCIDENT PROTON

Let us first demonstrate that a modest decrease in the neutrino production rate per incident proton between the beginning and the end of the proton pulse can explain the OPERA anomaly. The proton pulse shape has a leading edge rise-time of about  $0.8 \mu\text{s}$  and a trailing edge fall-time of about  $0.4 \mu\text{s}$  and approximately a flat top during the  $9.3 \mu\text{s}$  in between (see Fig. 11 of [1]). For simplicity, let us approximate the proton pulse shape by a rectangular pulse of duration  $\Delta t = 10.5 \mu\text{s}$ . Let us also assume that due to the change in the effective column density in the graphite target along the beam direction, the neutrino production rate per incident proton decreases linearly with time during the pulse. Consequently, the neutrino pulse shape becomes  $N(t) = N(0) - (\Delta N/\Delta t)t$  where  $\Delta N = N(0) - N(\Delta t)$ .

For a small change,  $\Delta N \ll N(0)$ , the mean time of such a neutrino pulse is given by,

$$t_m(\nu) \simeq \frac{\Delta t}{2} \left( 1 - \frac{\Delta N}{6 N(0)} \right). \quad (2)$$

The observed lead time of 60.7 ns in the mean arrival time of the neutrinos requires that the effective column density encountered by the proton beam decreases by  $\approx 7\%$  during the proton pulse.

### III. THE TARGET RESPOND TO THE BEAM

It would be presumptuous to calculate in detail the changes that take place along the beam path in the CNGS target during the  $10.5 \mu\text{s}$  proton pulse. Thus, we shall limit ourselves to simple estimates.

In the OPERA experiment the beam consists of 400 GeV protons extracted from the CERN Super Proton Synchrotron (SPS). The beam cycle is typically 6 s. There are two extractions per cycle, each  $10.5 \mu\text{s}$ , separated by 50 ms. Each extraction has  $2.4 \times 10^{13}$  protons, which carry  $\simeq 1.5 \times 10^{13}$  erg. The beam is nearly cylindrical with a diameter of 0.5 mm.

The target is 2 m long sealed container, which contains 13 graphite rods 100 mm long each. The first two have 5 mm diameter and the rest have 4 mm diameter. The total weight of the graphite is  $\sim 41$  g (for specific density of  $2.3 \text{ g cm}^{-3}$ ). The specific heat of graphite is  $0.17 \text{ calories/g}^\circ\text{K}$ , i.e.,  $7.1 \times 10^6 \text{ erg/g}^\circ\text{K}$ . A very large number of disks outside the container cool the target by heat exchange with the room temperature during the 6 s cycle.

Most of the prompt energy loss is through the escape of energetic particles which are produced in the proton initiated showers within the target. However a significant fraction of the energy deposited in the target, ( $\sim 10^{12}$  erg) does not escape during the  $10.5 \mu\text{s}$  pulse and heats the target to a very high temperature. The rising temperature decreases the target density, in particular along the beam direction. Well below the Graphite melting

temperature ( $\sim 3650^\circ\text{K}$ ), the thermal linear expansion coefficient of graphite is  $\sim 7.9 \times 10^{-6} (\text{K})^{-1}$  yielding  $\sim 4\%$  column density decrease at roughly  $2500^\circ\text{K}$ . Although, the thermal expansion coefficient of the target at such high temperatures is not well known, a reduction of 7% (see section 2) in the effective column density of the graphite target along the beam path at the end of the proton pulse seems plausible. The thermal radiation from the container and the disks cool the target during the 6 s cycle back to its much lower initial temperature.

### IV. CONCLUSIONS

It has been noticed before (e.g. [2]), that the assumption of the same temporal profile of the neutrino pulse as that of the proton pulse could be responsible for the neutrino speed anomaly, which was measured by the OPERA collaboration. In this short note we have proposed a plausible origin for a difference between the proton and neutrino pulse shapes and we showed that it could have led to the neutrino speed anomaly reported by OPERA. In particular, we predict that once the extracted  $10.5 \mu\text{s}$  proton pulses in the CNGS will be replaced by a few ns pulses the neutrino speed anomaly will disappear.

**Acknowledgment:** We would like to thank Jacques Goldberg for providing us with useful details on the OPERA experiment.

---

[1] T. Adam, et al. (OPERA Collaboration), 2011, arXiv:1109.4897

[2] J. Knobloch, 2011, arXiv:1110.0595